Hybrid technique for reduction of environmental magnetic field noise

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1 Introduction

There have been extensive studies on high-T_c SQUIDs that are fabricated from high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) films and utilize grain boundary junctions formed on a bicrystal-boundary or a step-edge of substrate. Single-chip magnetometers of high-T_c SQUID coupled with thin-film pickup loop(s) have been developed to have low field noises below 100 fT/Hz$^{1/2}$ [1,2]. With such sensitivities, it is capable to measure MCG signals for diagnosis of cardiac diseases.

In biomagnetic recordings, low-frequency noise (typically at 1-100 Hz) of the measurement system is crucial, including the system and environmental magnetic field noises. Magnetically shielded rooms (MSR) are commonly used in clinical examination of MEG, where residual environmental noise below 100 fT/Hz$^{1/2}$ is readily obtained with multi μ-metal layer shielding. However, such heavy-shielded room is not suited for MCG measurement system from the requirements of low cost, lightweight, and small space.

We have been studying the noise reduction scheme that utilizes passive *soft shielding* and active compensation of environmental field noises. We refer here to *soft shielding* as the shielding of order of 20 dB that can be attained with single μ-metal layer surrounding, *i.e.*, simplest MSR. In this paper we describe different methods of field detection and active compensation. A novel scheme is proposed using a normal conducting detection coil and a compensation coil, both of which are magnetically coupled to the soft-shielded MSR. MCG signals were successfully recorded within the soft-shielded MSR when this active compensation was applied.

2 Principles and methods

2.1 MSR for *soft shielding*

Figure 1 shows an example of environmental field noise in our laboratory measured with a flux gate magnetometer, where the field spectrum of MCG signal, which had been measured within a high performance MSR for MEG use, is also shown for comparison. If we assume 100 fT/Hz$^{1/2}$ intrinsic field noise of high-T_c SQUIDs for measurement of MCG signals, we need more than 40 dB attenuation of continuous background noise between 1 and 100 Hz. Further, we need attenuation of 80-100 dB for line-spectrum noises, especially 50 Hz noises, which arise from electric lines and devices near the MSR.

As the scheme to reduce such field noises for MCG measurement, we consider here active compensation combined with a MSR of soft shielding. For this purpose, a prototype MSR was fabricated and used in this study. It utilized single μ-metal layer (1 mm thickness), which was expected to have attenuation of about 20 dB at low frequencies. The μ-metal layer was fixed on a wooden-plate frame, which finally formed a cubic shielded space of 1.8 m × 1.8 m × 1.8 m. Thin Cu foil (60 μm thickness) was also used for rf-wave shielding. A door of a size of 60 cm × 120 cm was equipped for the entry. The total weight of the MSR was 500 kg.

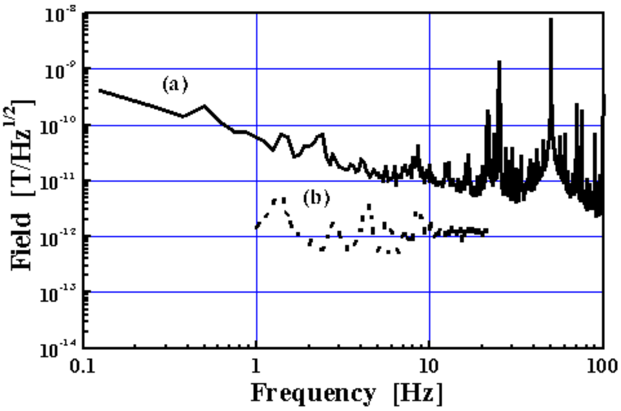


Figure 1: *Frequency spectrum of a) environmental field noise measured with a flux gate magnetometer. b) MCG signal (dotted line between 1 and 20 Hz) measured with a high-T_c SQUID magnetometer inside a heavy-shielded room.*

2.2 Active compensation

In the active compensation combined with the MSR, we aimed to obtain attenuation of 20 dB or more at low frequencies, in addition to the 20 dB shielding by the MSR, using a magnetic field sensor outside the MSR, *i.e.*, without use of SQUID. In this scheme, the active-shielded MSR would be equivalent, at much lower cost and weight, to the conventional MSR that has two or more μ-metal layers. We assume hereafter to attenuate vertical component of environmental ac fields.

Field sensing with flux gate magnetometer

We first consider the method using a flux gate (FG) magnetometer and a compensation coil wound around the MSR. Figure 2a schematically illustrates this compensation and the flow of field signal, where the broken line indicates transmission of the field through space. Based on this signal flow, the residual field B_{in} inside the MSR may be given by Eq. (1)

$$< B_{in} >^2 = \left[\{1-\alpha(\omega)\}s(\omega)B_{ex}\right]^2 + \left\{\alpha(\omega)s(\omega)B_n\right\}^2 .$$

Here, B_{ex} is the external field, B_n is the intrinsic noise of the FG magnetometer, $\alpha(\omega)$ is the transfer function of the compensation system, and $s(\omega)$ is the transfer function of the MSR, *i.e.*, shielding factor. The bracket of $<B>$ indicates *rms* value of the field. The attenuation of the field noise is obtained by adjusting the gain of the amplifier to be $\alpha(\omega) \approx 1$. The lowest attainable field noise may be of the order of $<s(\omega)B_n>$.

We prepared a set of 5-turn coils wound tightly around the MSR wall horizontally at the top and the bottom. These two coils were connected in series and served as the compensation coil, which was fed with current to generate the compensation field. A FG magnetometer having a sensitivity of about 5 pT/Hz$^{1/2}$ was placed at a location 3m distant from the MSR wall at the middle height.

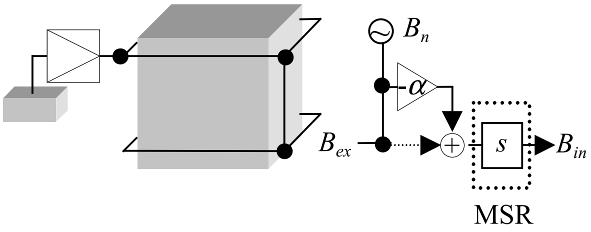
Field sensing with normal conduction coil

Normal conduction coil is an alternative of the FG magnetometer to detect the field noise. We devised a scheme using a detection coil tightly wound around the MSR wall at the middle height and the serial compensation coils wound at the top and bottom of the MSR. Figure 2b illustrates this compensation method with schematic signal flow, where $\gamma(\omega)$ is the field-to-voltage conversion function of the detection coil and $\alpha(\omega)$ is the serial transfer function of the amplifier, the integrator that converts time-derivative signal to magnetic field, and the compensation coil. Assuming high permeability of the μ-metal wall of MSR, there is a tight coupling of flux between the compensation and detection coil to form a closed feedback loop. Then, the residual field inside the MSR may be given by Eq. (2)

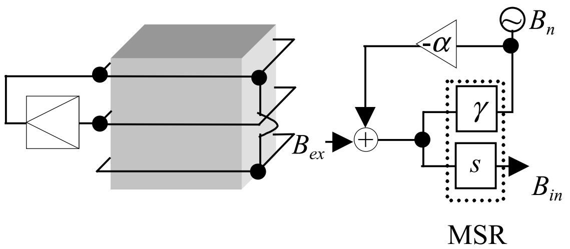
$$< B_{in} >^2 = \left\{ \frac{s(\omega)}{1+\gamma(\omega)\alpha(\omega)} B_{ex} \right\}^2 + \left\{ \frac{s(\omega)}{\gamma(\omega)} B_n \right\}^2 .$$

For high open loop gain of $\gamma(\omega)\alpha(\omega) >> 1$, the field noise is attenuated by the product of the shielding factor and the open loop gain. Because of the feedback operation, the attenuation is insensitive to the magnitude of $\alpha(\omega)$. Therefore, precise adjustment of the loop gain is not necessary, like the feed-forward compensation in Fig. 2a.

A normal conduction coil, as a field sensor, was wound around the MSR wall at the middle height using 0.5 mm thick Cu wire. Sixty-turns coil had a resistance of 50 Ω. The serial compensation coil was the same as the one used in the feed-forward method using the FG magnetometer.



(a) Feed-forward Compensation



(b) Feed-back Compensation

Figure 2: *Schematic drawing and signal flow of a) feed-forward compensation using a FG magneto-meter and b) feedback compensation using a normal conduction detection coil.*

2.3 Measurements of field noise and MCG

In order to evaluate the residual field noise in our *soft shielding* MSR with and without active compensation, we used direct coupling SQUID magnetometers. They were made of YBCO films formed on $SrTiO_3$ bicrystal with 30° misorientation angle. The SQUID had a main loop made of 5 μm-wide strip-line with 10 μm × 80 μm hole, which had an inductance of 100 pH [3]. This SQUID loop was located inside a large hole of a square-washer pickup coil having inner and outer dimensions of 3 and 9 mm, respectively. The whole area of the YBCO film of the pickup coil was filled with fine structures composed of 5 μm-wide lines and 5 μm × 45 μm slots [4]. Because of this slotted structure, the magnetometer could be operated in the residual earth field in the *soft shielding* MSR and even in an environment without shielding. The sensitivity of the magnetometers was 100-250 fT/Hz$^{1/2}$ at the white noise level.

The SQUID magnetometer was mounted in a capsule and located at the bottom of a liquid nitrogen dewar. The residual field noise within the MSR was measured at the FLL output of the SQUID. When we measured the MCG signal, a subject lay supine beneath the dewar and the real time trace was recorded.

3 Results and discussion

3.1 MSR and feed-forward compensation

The measured shielding factor of the single μ-metal layer MSR was about 10 below 10 Hz, slightly different among vertical and two horizontal directions, and increased with frequency to 40-70 at 100 Hz. This frequency dependence agreed with the measured current-to-field transfer function of the serial compensation coil, which had a cutoff frequency of 30 Hz. Our *soft shielding* MSR can be represented by the 20 dB attenuation and 30 Hz low-pass characteristic.

Figure 3 shows the results of feed-forward compensation using the FG magnetometer located outside the MSR, where the spectra of residual field noise in the MSR measured before and after compensation are compared. Low frequency noise was reduced by 10 dB, but noise peaks at 2-6 Hz were almost remained. These peaks originated in the vibration of the floor and the induced oscillation of MSR walls. In the measurements, we limited the compensation signal to frequencies below 10 Hz; otherwise residual fields at intermediate frequencies was increased by compensation, because of the low-pass characteristic of the current-to-field transfer function of the compensation coil.

As proved in this measurement, the disadvantages of the use of FG magnetometer are that the field is not sensed at the desired site where the filed noise should be attenuated, and that the effective frequency range is strongly limited by the low-pass characteristic of the MSR. Although this type of compensation is used with commercial multi-layered MSR, significant attenuation is obtained at very low frequencies below 1 Hz [5].

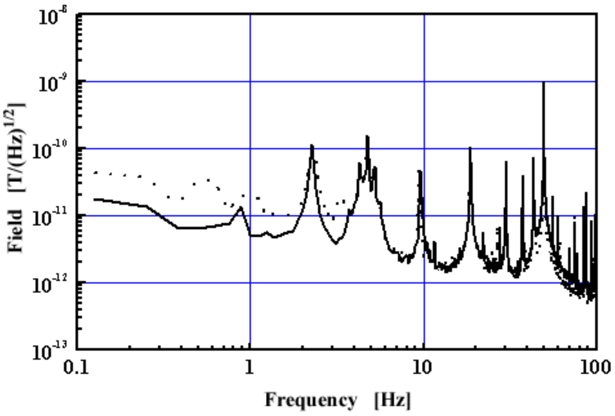


Figure 3: *Residual field noise in the MSR with (solid line) and without (dotted line) feed-forward compensation using a FG magnetometer.*

3.2 Compensation with normal coil

The feedback compensation using the normal conduction coil was very successful. As illustrated in Fig. 4, attenuation was obtained in a wide frequency range from well-below 1Hz to more than 10 Hz. Further, peak noises within this frequency range were effectively attenuated more than 20 dB, which indicates that the normal conduction coil that is magnetically coupled to the MSR senses the noise arising from its vibration. Such effective attenuation was obtained with rough adjustment of the loop gain because of the feedback operation. A few previous studies describe the use of normal-conducting detection coil, which is allowed to couple with the compensation coil but not directly with MSR [6,7]. The reported noise reduction is not efficient.

The field sensitivity, *i.e.*, intrinsic noise, of our feedback compensation is given by $<B_n/\gamma(\omega)>$, where B_n is composed of thermal noise of the normal conduction coil and the amplifier noise. Here, the amplifier used had noises of 10 and 3 × 10^{-9} V/Hz$^{1/2}$ at 1 and 10 Hz, respectively. Using the measured field-to-voltage conversion ratio ($\gamma(\omega) \approx 4 \times 10^5$ V/T at 50 Hz) of the detection coil, the field sensitivity was estimated to be 1.3pT/Hz$^{1/2}$ at 1 Hz and 40 fT/Hz$^{1/2}$ at 10 Hz. Therefore, the large area detection coil, that surrounds the MSR, has much higher field sensitivity than the FG magnetometer.

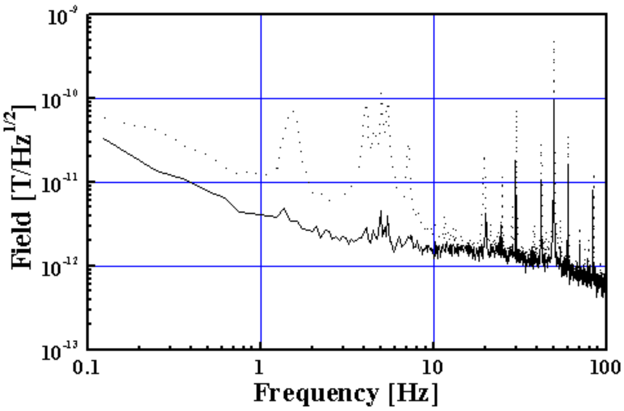


Figure 4: Residual field noise in the MSR (upper) with (solid line) and without (dotted line) feedback compensation using a normal-conducting detection coil.

3.3 MCG recordings

Figure 5 shows the real-time trace of MCG signal recorded in the MSR, where the output of the SQUID was low-pass filtered below 40 Hz to cut high-amplitude 50 Hz noise.

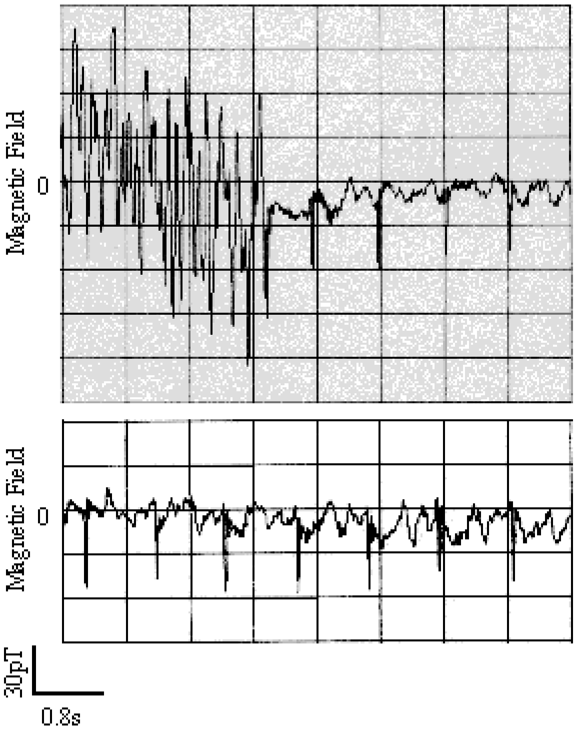


Figure 5: Real-time trace of MCG signal recorded in the MSR. The feedback compensation was operated at about the midpoint of the upper trace and stabilized in the lower trace.

Without feedback compensation (left side of the upper trace), signal was dominated by the low frequency vibration noises. When the compensation was operated (right side of the upper trace), the noises were greatly suppressed and MCG signals of about 60 pT in peak-to-peak appeared in the trace. After the compensation was stabilized, P, QRS, and T waves were discerned (lower trace).

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